Fracture of a Marine Gear (A)

One afternoon in May, 1954, work at the Consolidated Plant in Long Beach, California was disrupted by what sounded like a small explosion. Mr. George Reynolds, a veteran materials engineer and head of the metallurgical laboratory of the plant recalled, "I was sitting at my desk working on a progress report when I heard the explosion. Not more than a couple of minutes had passed before I got a phone call from the shop foreman to come and take a look at a large gear that had cracked after being welded together. I went to the shop and found that the gear that had cracked was a large 93" O.D. low speed reduction gear that we were making for Atlantic Yards, an East Coast shipbuilding firm (see Exhibit 1). The foreman explained to me that his men had welded together the side plates and the rim of the gear and had allowed the assembly to cool. When they inspected the weld after it cooled, they found circumferential cracks that followed the weld fusion line all around the inside of the rim (see Exhibit 2). They explored several of the larger cracks by chipping to determine how severe the damage was. The cracks sppeared to be quite extensive in length so the shop foreman decided to machine them out on a boring mill and then fill in the damaged areas by welding.

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* All names of companies, individuals, places and dates in this case are disguised.

Prepared in the Design Division of the Department of Mechanical engineering by William J. Clemens under the direction of Professor O.Cutler Shepard with financial support from the National Science Foundation.

When approximately three quarters of the outside fillet weld was removed, the crack along the fusion line suddenly propagated completely through the rim, making a noise that sounded like a small explosion. I measured the crack and found that it was as much as 5/32" wide in some places. The foreman had called me in on the problem because it was the job of my section to investigate and recommend corrective action of materials failures.

This is the first time since the war (WW II) that we had manufactured any of these large gears," Mr. Reynolds continued. "The main shop of our No. 2 plant in San Diego, where these gears were normally manufactured, had been destroyed in a large fire, so they hadn"t been able to make any gears for several months. To satisfy their contracts, management transferred their work up to our main plant here in Long Beach. At that time, we primarily were manufacturing pressure vessels and hydraulic power systems and weren't in the gear business at all. We had the equipment needed for the work, however, so we made the gears for about a year while our San Diego plant was being repaired."

Consolidated, Long Beach

The work done in Mr. Reynolds' Metallurgical Laboratory varies from consulting work with the design engineers in the different departments at Long Beach to the testing of incoming materials. There are two main departments in Consolidated's Pacific Division with which Mr. Reynolds' section works -- the power transmission department and the commercial products department. The power transmission department designs and manufactures reduction gearing, gearmotors and pressure vessels. The commercial products section manufactures hydraulic power systems and power tools, such as impact wrenches, power drills and portable saws.

The Metallurgical Laboratory writes the specifications for and makes the layouts for non-destructive testing and welding. They perform

non-destructive testing and welding. They perform non-destructive tests such as X-ray and ultrasonic tests, of castings to detect unacceptable parts and to help the foundry develop better casting procedures. Perhaps one of the most important jobs that Mr. Reynolds' group performs is the metallurgical investigation of products that failed during manufacture. Here they perform both chemical and physical tests of the failed material to determine the cause(s) of failure. They are usually the first ones called into the case to find the source of the problem so that production can be resumed as soon as possible.

The Gears

The gears that Consolidated were manufacturing at the time of the "explosion" were low speed and high speed reduction gears for marine equipment. They ranged in size from three to ten feet in diameter and in width from about one to three feet. Low carbon steel discs (center plates) were welded to low carbon steel hubs and reinforced with steel ribs. This assembly was then welded to the heat treated alloy steel rim. Exhibit 3 shows two views of a gear similar to the one that cracked. The alloy steel rims were ordered from a vendor and Consolidated specified their alloy composition, Brinell hardness, and heat treatment. The discs (center plates) and ribs were flame cut from rectangular plate steel which was bought from another vendor. The hubs were bought separately as rough machined forgings.

The alloy composition specified for the gear rims was as follows: Carbon, .35% max.; Manganese, .40-80%; Phosphorus, .04% max.; Sulphur, .045% max.; Silicon, .20-.35%; Molybdenum, .30-.50%; and Vanadium, .10-.25%. The required Brinell hardness was 223 to 269, with a range no greater than 34 numbers. Typically, the rims were first heated to 1600° F, quenched, then drawn at 1170° F.

When the rims reached the Consolidated plant, they were preheated to about 400° F then welded manually to the center plate assembly with single J, fillet reinforced circumferential welds.

After the large gear rim failed, Mr. Reynolds made a visual inspection of the damaged gear, then began performing a series of standard materials tests on it. The results of his inspection and tests on the damaged rim are shown in Consolidated Metallurgical Report 728, Exhibit 4. These test results showed that the gear rim material generally met Consolidated's specifications, i.e., the alloy composition, hardness and reported heat treatment were in line with what Consolidated had ordered. The material was found to have a low impact strength, however, which indicated that it had a low notch toughness. Mr. Reynolds speculated that this low notch toughness was a contributing factor in the propagation of the cracks in the welded material.

Mr. Reynolds took samples from the gear rim for examination of the microstructure. A 2% Nital etch revealed under a 100X microscope that the rim had a fairly coarse ferrite and pearlite microstructure. This indicated to him that the rim had been slack-quenched, the relatively slow cooling rate of which could account for the rim's poor impact strength. The rim material, as received, had a Charpy impact test strength of 3-5 ft.-lbs. while another specimen from the same rim, after being water-quenched and drawn, had an impact strength of about 70ft-lbs. A complete description of Mr. Reynolds' investigation of this gear can be found in Exhibit 4.

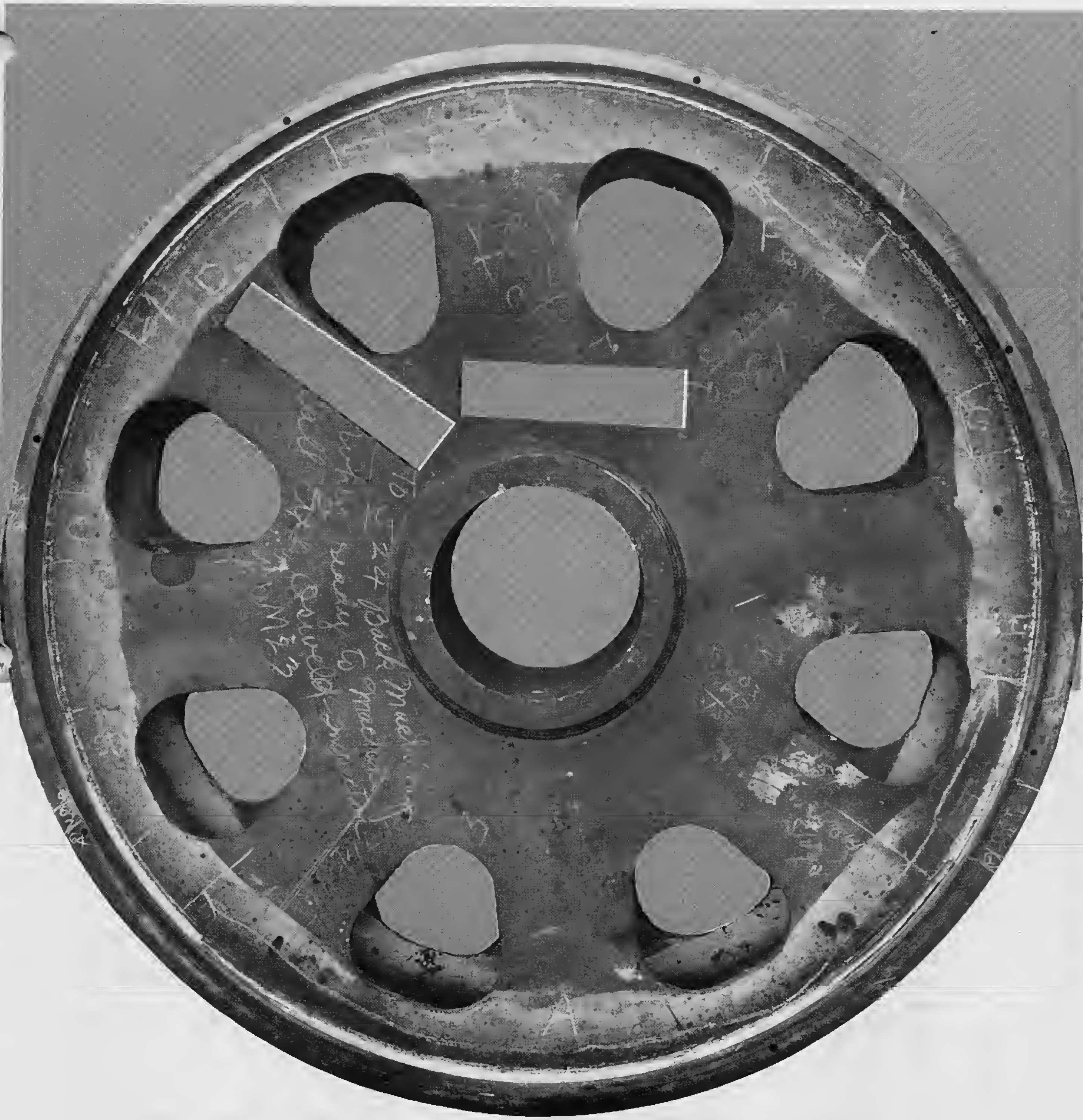
After reviewing the data he collected for Report 728, Mr. Reynolds concluded that the gear rim material for future rims must have a higher noth toughness. To achieve this, he recommended that the specification for the gear rims be changed to require that all future gear rims be water-quenched for a faster cooling rate and that a minimum impact strength value be incorporated in the gear rim specifications. Mr. Reynolds also recommended that the type of weld be changed from a single J, fillet reinforced weld to a double J, fillet reinforced weld. He felt that the shrinkage stresses for this type of weld would be much smaller than those for a single J weld.

One immediate effect of the new requirement was that Consolidated's principal supplier of gear rims, the Tressle Steel Company, could not meet the new specifications. Some of Tressle Steel's equipment appeared to be inadequate for this work. Also, the rims sometimes would not be transferred quickly enough from the heat treating furnace to the quenching tank, thus compounding the problem. Tressel Steel was unwilling to upgrade its plant to meet the new requirement, so it had to be crossed off the list of potential suppliers.

Mr. Reynolds explained, "The measures that we proposed back in 1954 weren't necessarily the best solutions to our problem. Those recommendations cut down the number of potential rim suppliers, which was a definite disadvantage. Cutting down the number of suppliers also cuts down the number of potential bidders on future contracts. Whenever you do this sort of thing, you are running the risk of having to pay higher prices for your merchandise. Furthermore, if we had a rush order for gear rims, it would be harder for us to get enough rims at one time from our principal supplier and we would have to look for another to help fill the order, which would be difficult with these restrictive specifications."

"We needed to find an alternative to our proposals that wouldn't have these disadvantages. We thought that there was probably some change we could make in the manufacturing of the rims or in the materials that we used in them that would solve our problem, but we didn't develop a new process or manufacturing technique at that time because these gears were the last ones that we would be making and we wouldn't have the opportunity to carry any such changes through to completion.

Most of the gears in the same shipment as the failed rim were already in some stage of welding. Since the first gear of this group had cracked as soon as it was welded together, Mr. Reynolds had to determine if the rest of the rims were adequate and, if not, if they could be salvaged by some kind of treatment.



Front view of 93-inch outside diameter low-speed gear that failed during manufacture.

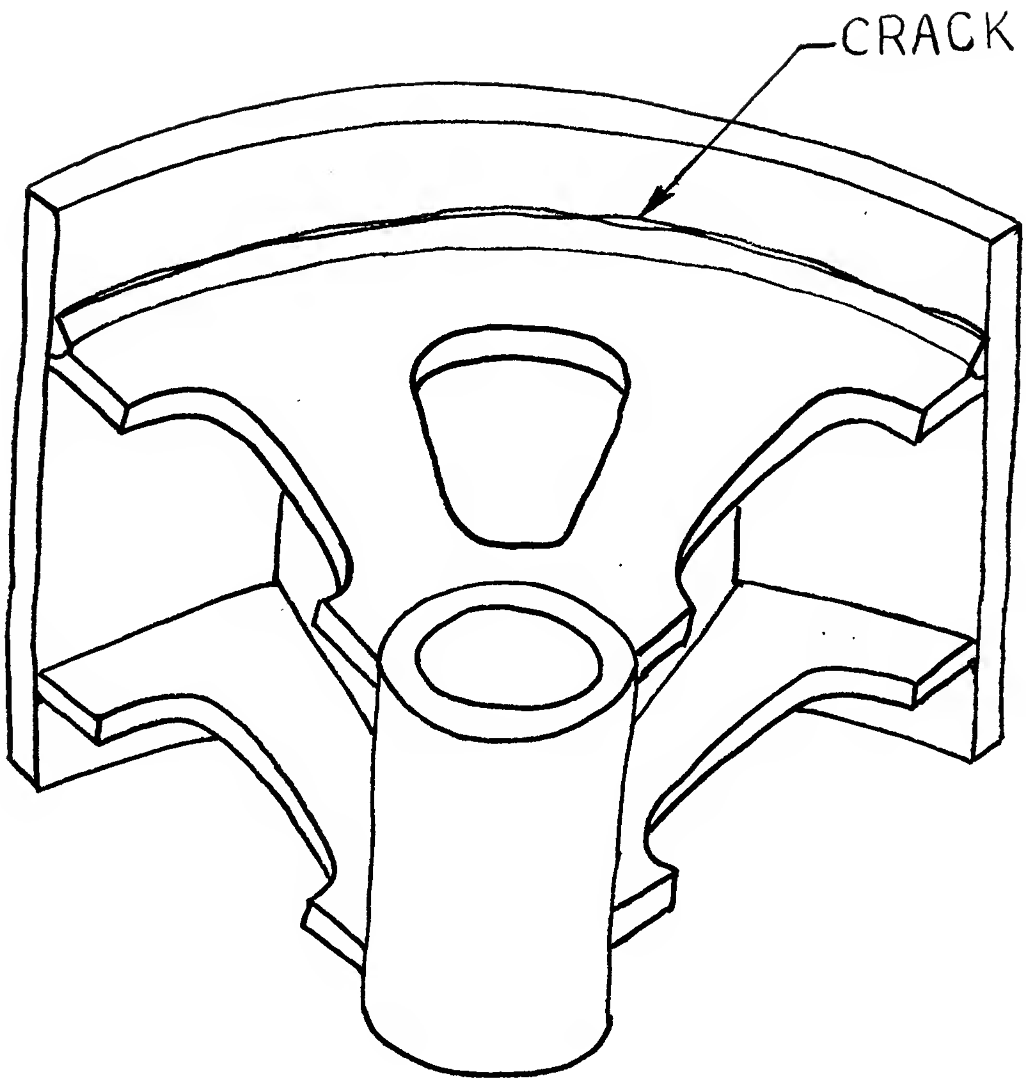
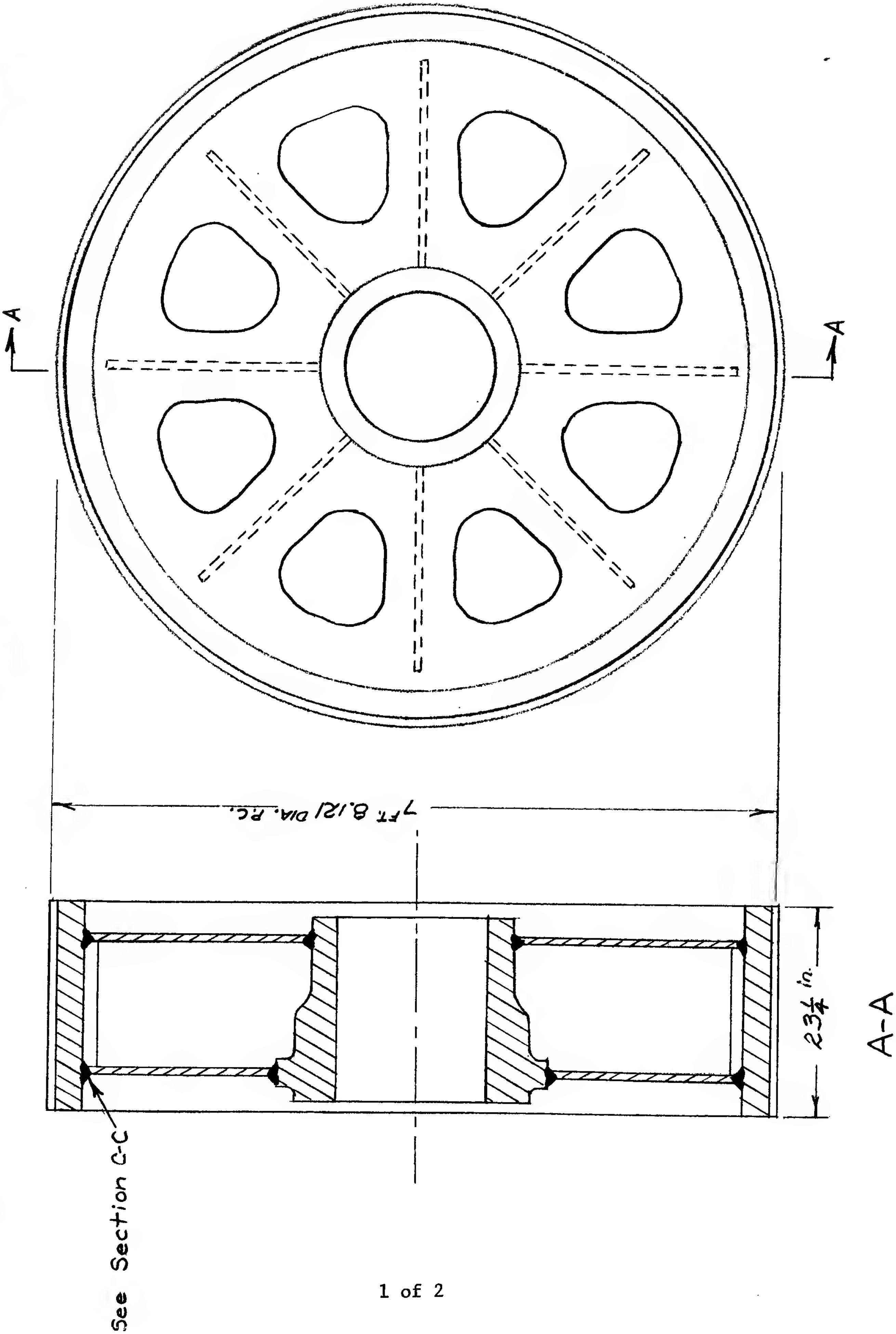
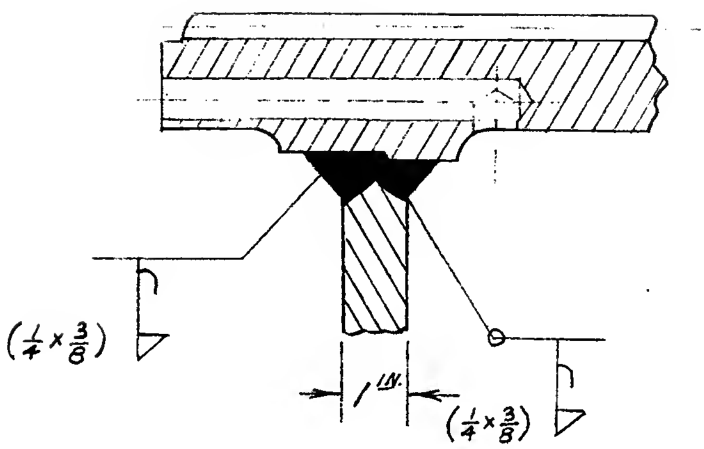


Exhibit 2. Casewriter's sketch of a typical sector of gear showing location and direction of cracks before weld was machined off and gear "exploded". Photographs of cracks after the weld was machined off are shown in Exhibit 4.



Slow speed gear wheel similar in type to the one that failed in 1955.



SECTION C-C

Detail drawing for Exhibit 3

CONSOLIDATED DYNAMICS CORPORATION LONG BEACH, CALIFORNIA

INVESTIGATION OF FAILURE OF LOW SPEED GEAR WHEEL DURING FABRICATION

Metallurgical Report No. 728

Exhibit 4. Text and selected exhibits from Consolidated Metallurgical Report No. 728. Names and contract numbers have been either disguised or deleted.

METALLURGICAL LABORATORY May 22, 1954

INVESTIGATION OF FAILURE OF LOW SPEED GEAR WHEEL DURING FABRICATION

An investigation into the cause of failure of a low speed gear wheel during machining following welding has been completed. Cracking of the gear rim adjacent to the outside rim weld was first encountered on one side during the making of this weld. Subsequently several areas were explored by chipping to determine extent of cracking. Since cracking was found to be quite extensive in length it was decided to machine out the cracks on the boring mill and reweld. No stress relieving was performed prior to machining. On removal of approximately three quarters of the outside fillet weld in the boring mill the fusion line crack suddenly propagated completely through the rim from I.D. to O.D.

Conclusions

Results of the investigation indicated that the failure of low speed gear wheel during fabrication was caused by a combination of the following factors:

1. Material welded had a high notch sensitivity as indicated by low impact strength.
2. Presence of multidirection shrinkage stresses common to a circumferential weld. The type of joint design used (single J with fillet reinforcement) results in higher weld shrinkage stresses than would be encountered using the double J with fillet reinforcement proposed by Long Beach.
3. Presence of hardened zone in heat affected area on last weld pass when made on rim. This condition can be alleviated by a change in pass sequence.
4. Undercut at edge of weld bead. Although care is now taken to avoid undercut, special effort must be made to avoid it on gear rim surfaces.

Any one or a combination of the above factors can lead to a brittle type of failure such as encountered here.

Recommendations to prevent a similar reoccurrence are listed at the end of the report.

Visual Examination

The extent of the main crack over a total distance of 96" on the circumference is shown in the following photographs:

1. Photograph 9462 - Crack originating at weld fusion line and extending through rim thickness on edge to O.D.
2. Photograph 9463 - Fusion line crack at widest section - approximately 5/32" wide.

3. Photograph 9464 - Crack at other end from that shown in Photograph 9462 ending in oil drain hole. Note separate crack in gear rim slightly below crack end.
4. Photograph 9466 - View showing end of crack from I.D. of rim.
5. Photograph 9467 - View showing other end of crack on I.D. of rim.
6. Photograph 9476 - Extent of cracks as revealed by magnetic particle inspection after failure. Section A covers extent of crack shown in the above photographs. Section B contains both undercut and cracking at fusion line of weld. Sections C, D, E, F, G and H are additional cracked areas in fusion line as shown by magnetic particle inspection.

Prior History

The gear rim was purchased from the Tressle Steel Company, Pittsburg Pa. It was identified as follows:

Long Beach
No. LB 180
Rough Machined Size 87-3/8" I.D. x 93" O.D.x
23 5/8" wide.

The supplier's chemical analysis is compared below with the Long Beach test results:

	Supplier's test	L.B. test	Required
C	.32%	.33%	.35% max.
Mn	.74	.70	.40-.80
P	.029	.015	.04 max.
S	.030	.030	.045 max.
Si	.26	.28	.20-35
Mo	.35	.31	.30-.50
V	.15	.15	.10-.25

Brinell hardness test made at the place of manufacture at four spots, 90° apart, on each side of the rim gave results as follows:

1	2	3	4	5	6	7	8
269	269	262	269	269	269	269	269

Required Brinell Hardness - 223 to 269 (Range no greater than 34 numbers.)

Results of Tests

Measurements of crack width at widest opening was 5/32" indicating roughly the amount of shrinkage stresses resulting from welding. In an effort to learn the nature of difficulties leading to failure transverse sections were cut across entire width of gear rim and weld. Photograph 9476 shows location of these test pieces marked 1 and 2 on gear rim edge, 180° apart. Section 1 , 8" wide and section 2 , 1-1/2" wide were flame cut radially from the gear wheel. A 1-1/2 wide slice machined from section 1 and section 2 were used for macroetch tests and Brinell hardness traverses. The remainder of section 1 was machined to remove both tangential and longitudinal tensile and impact specimens.

Longitudinal and tangential tension and impact tests gave the following results:

	Longitudinal	Tangential
Tensile strength, psi	124,000	121,500
Yield strength, psi 0.2% offset	99,000	95,000
Elong. in 2 inches, %	19.5	22
Red. of area, %	41	57
Izod impact, ft-lbs.		
ASTM Type D	6.0, 5.5	6.0, 6.0
ASTM Type Z	5.5, 7.0	3.5, 4.0

Figure 1 shows the results of Brinell hardness traverses of sections 1 and 2 taken 180° apart. Figure 2 shows the results of Rockwell C hardness readings taken in heat affected zone adjacent to weld. Note that the overlaying pass of weld on rim material was Rockwell C 35, and that the underlying passes had been annealed by subsequent beads to Rockwell C 25 to 29.

Photograph 9493 shows the macrostructure of the sections used for the Brinnel tests above. These sections were etched with ammonium persulfate. Also included is a deep acid etched (50% HCL) specimen from the rim centerline to within 4" of the weld joint.

The macroetch tests revealed the overall soundness of the gear rim and welded joint. In general, a denser structure was present at the O.D. The weld itself was good at the areas etched with the exception of 2 small flux inclusions. Note, however, the path of fracture originating at the edge of outside rim weld (partly machined away) and progressing along a curved line into the rim more or less parallel to rim axis. The direction of the path of fracture was probably favored by the direction of the welding shrinkage stresses present.

Figures 3 and 4 show the microstructure of the gear rim material and welded joint. Figure 3 shows the unetched and etched microstructure of the gear rim material in the transverse direction.

Figure 4a shows the fracture surface in the heat affected zone adjacent to the weld and Figure 4b shows the coarse-grained hardened structure immediately adjacent to weld metal.

Discussion of Results

A review of the information above indicates that this particular gear rim is on the "high" side of chemistry and hardness, although conforming to specification requirements. Material is not purchased to tensile or impact properties, however, tensile properties are in line with results of tests made at Pittsburgh. Impact tests are lower than comparable tests made at Pittsburg on rim material made from M.S. 3905, and indicate that material is "notch sensitive".

It is believed that fracturing of the gear rim took place somewhat as follows. Cracking first occurred during welding in heat affected zone adjacent to weld on rim and was probably "triggered" by a small amount of undercut or by hardened area. The cracks propagated a short distance into the rim. At this point it was decided that cracks would be removed by machining rather than by chipping and grinding since they were of considerable length. During the removal of fillet weld in boring mill the initial cracks suddenly propagated to complete fracture through gear rim. Apparently the residual stresses which tended to hold the gear rim at a smaller diameter were released with the removal of the restraining fillet weld forcing propagation of the original cracks completely through the rim thickness. Residual milti-directional stresses of the type existing in a circumferential weldment can lead to brittle failure especially when combined with a "notch sensitive" condition of the material as revealed by the low impact strength values obtained.

Recommendations

As a result of this study the following recommendations are made:

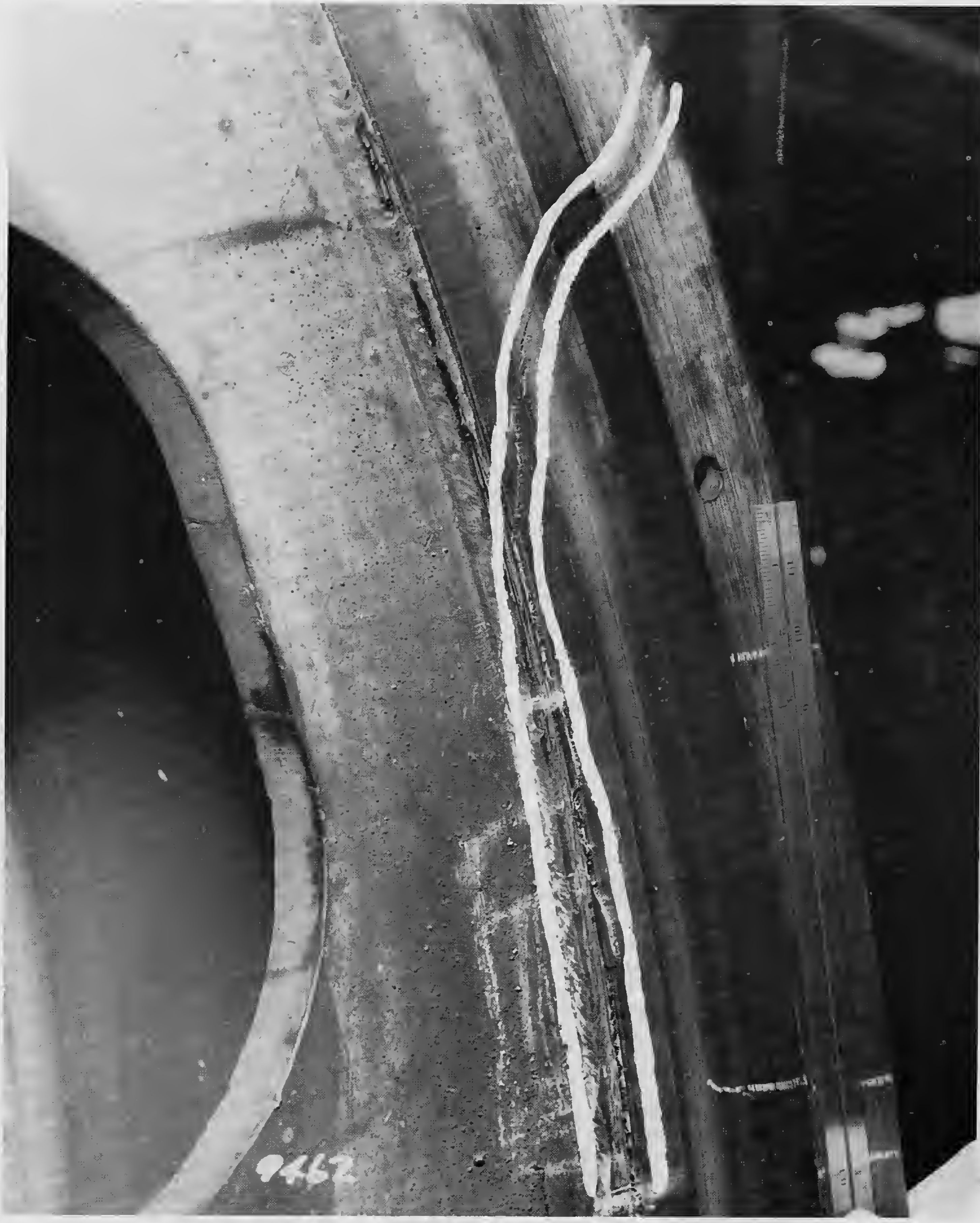
1. Gear rim material for replacement and future rims must have higher impact strength to decrease notch sensitivity and to guarantee satisfactory performance in service. M.S. 3905F must be revised to specify a water quench to insure satisfactory impact strengths. A minimum impact strength value should be incorporated in the specification as a check on the adequacy of steel making and heat treating practices.

2. Joint design should be changed to a double J with fillet reinforcement to reduce weld shrinkage stresses, as previously proposed. It should be pointed out that any welding procedure that will reduce residual stresses resulting from weld shrinkage is advantageous in preventing the type of failure encountered.

3. When making welds on joints involving alloy steel wherever possible use a bead sequence which will allow last bead to be made on weld deposit or on mild steel. This will allow overlaying beads to anneal underlying weld on alloy material reducing the hardness in the heat affected zone.

4. Avoid undercut along weld edge which can act as a notch to "trigger" cracking.

5. On subsequent gear wheels if cracking is encountered, stress relieve prior to removal of defects to avoid propagation of cracks.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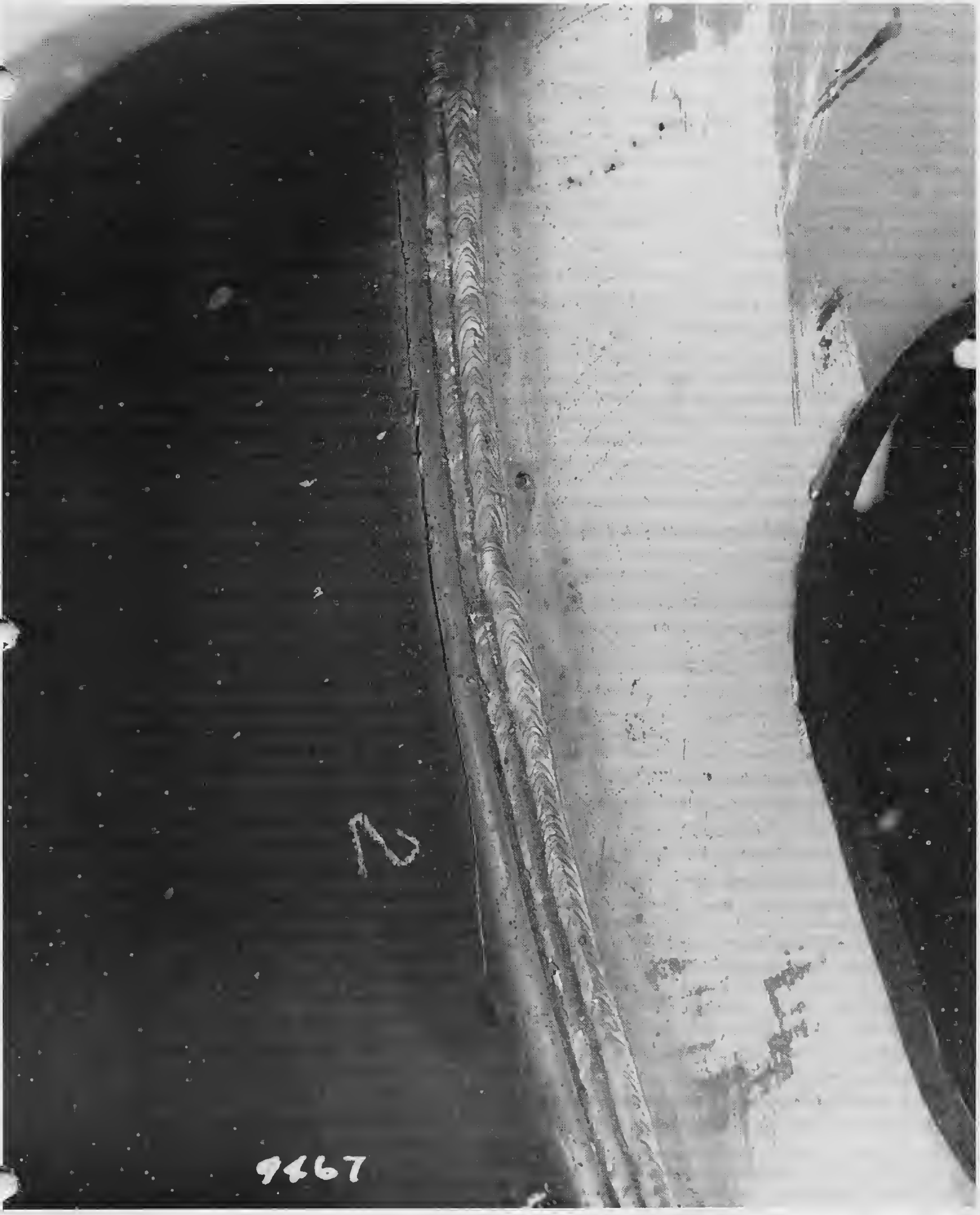
9466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Fracture of a Marine Gear (B)

Not all the gear rims Consolidated had received from the Tressle Steel Company were for the Atlantic Yards contract. Of the group of rims that Mr. Reynolds suspected of being slack-quenched, three had been supplied for other contracts. He chose two of the gear assemblies and a gear assembly which had been scrapped by Atlantic because of some non-metallic inclusions on its shaft and had them re-heat treated to see how much could be done towards improving the impact properties of the rims without harming the rest of the assemblies. He performed the following heat treatment on the test (cf. Report 729, Exhibit 5) :

1. Heat to 1550°F.
2. Quench vertically in circulating brine solution to 150°F.

3a. Draw 6 hours at 1200°F (heat 64586), or
 b. Draw 6 hours at 1225°F (heat 53030).

4. Furnace cool from draw.

As mentioned in Consolidated Metallurgical Report 729, Mr. Reynolds performed dimensional measurements before and after heat treatment. After heat treatment, the gear assemblies were cut into three pie-shaped sections to obtain macrospecimens of the rim and rim welds and of the hub and hub welds at three locations 120° apart on the gear. He also removed tensile and impact specimens from the rim before and after the heat treatment to assess the effects of that treatment on these properties.

Report 729 shows that the tensile properties of the rims tested after re-heat treatment were up more than 20 ft-lbs from their pre-treatment values. Dimensional measurements showed that all the unfinished gear assemblies from one of Tressle Steel's heats (heat 64586) could be salvage heat-treated since enough stock remained on the rims for finish machining. However, the rims which had already been finish machined would have to be scrapped because there wouldn't be enough material left for final machining. Mr. Reynolds found that the diametral shrinkage varied from about .037" on the journals to .065" on the rims.

Because of the favorable outcome of these tests, Mr. Reynolds recommended in Report 729 that all of the unfinished rims from heat 64586 (which had the slack-quenched rims) be salvaged by the heat treatment used on the test gears. After obtaining the approval of the Atlantic Yards, Consolidated was able to successfully finish all of the remaining gears it had on order for its contract. After completing this order, Consolidated's San Diego plant, having been rebuild, resumed full production of Consolidated's gears.

CONSOLIDATED DYNAMICS CORPORATION LONG BEACH, CALIFORNIA

METALLURGICAL INVESTIGATION OF GEAR RIM MATERIAL

Metallurgical Report No. 729

Exhibit 5. Text and selected exhibits from Consolidated Metallurgical Report No. 729 Names and contract numbers have been either disguised or deleted.

METALLURGICAL LABORATORY June 1, 1954

METALLURGICAL INVESTIGATION OF LSD GEAR RIM MATERIAL

A study has been made of the strength properties and microstructure of gear rim material on which a brittle failure had occurred during fabrication in the shop. This failure was reported in Long Beach Metallurgical Report No. 728, dated May 22, 1954. Failure was mainly attributed to the high notch sensitivity of the material as indicated by the low impact strength.

Since preliminary impact tests revealed that material was of poor quality it was deemed necessary that further tests be made to determine adequacy of material for service. A survey indicated that there were four low speed gear rims, 20 high speed gear rims in process of manufacture and one low speed rim scrapped due to being out-of-round from the questionable heat (Ht. No. 64586). Three of the high speed gear rims had been supplied for commercial gears and the remainder (17) were for the Atlantic contract. Subsequently, high speed gear wheel assemblies, L.P.H.S. gear wheel LB 170 (Ht. 64586), L.P.H.S. gear wheel LB 169 (Ht. 64586), and H.P.H.S. gear wheel LB 162(Ht.53020), which was finish turned and had been scrapped by Atlantic as a result of non-metallic inclusions on shaft, were salvage heat treated. Tests made following heat treatment included distortion measurements, magnetic particle inspection, and the removal of test specimens for tangential and longitudinal impact and tensile tests, macro and micro examination. Tensile tests were also made of hub forging and rib plates after heat treatment.

Conclusions

Gear rim material from Heat No. 64586, supplied by the Tressle Steel Company, was of poor quality as indicated by low impact strength. The low impact strength was mainly attributed to the "slack"quench obtained in oil quenching, although other heats of steel had better properties with an oil quench. A water quench and draw, however, increased impact properties in the case of two heats of steel tested. Since rim material from Ht. 64586 was unsuitable for use and rims were welded into assemblies, trial heat treatment of test assemblies were made in an attempt to salvage them. This heat treatment consisted of a water quench and draw. Test results indicated that assemblies could be salvage heat treated without appreciable distortion and with considerable improvement in the impact properties of rim forgings. Heat treatment of hub forgings and rib plate materials did not lower their properties below minimum specification requirements and, in fact, improved strength properties. The type of heat treatment applied will not only improve mechanical properties of all materials including welds, but will erase the heat affected zone adjacent to the welds. In addition, superior dimensional stability will be obtained.

Procedure

In order to determine quality of all gear rim material supplied by Tressle Steel Company impact tests were made on the following gear rims representing all heats supplied on all orders:

"LB" No.	Ser. No.	Heat No.	Size	Remarks	No. of Rims in Heat
LB 180	244639	64586	Slow Speed	Fractured in fabrication.	25
LB 188	246698	64586	H.P.H.S.	Scrapped for test-as-rec'd.	
LB 169	242786	64586	L.P.H.S.	Scrapped for test-salvage heat treated.	
LB 164	239769	53150	L.P.H.S.	Scrapped due to forging crack.	11
LB 165	238494	75102	Slow Speed	Scrapped due to low hardness	4
LB 162	239768	53020	H.P.H.S.	Scrapped due to defective hub-salvage heat treated.	21
None	-	64684	H.P.H.S.	Tests made by Tressle	6

The status of manufacturing on all rims for gear contracts Nobs 1814, Nobs 1865 and Nobs 1914 is as listed in Table I.

Heat treatment of all rims supplied is as listed in Table II. It should be noted that 4 rims were water quenched and the remainder were oil quenched. Three of the four rims were for commercial gears and of greater section thickness, hence were water quenched. The microstructures of water quenched rims were checked for adequacy of quench.

Salvage heat treatment of test gear assemblies was as follows:

1. Heat to 1550°F.
2. Quench vertically in circulating brine solution to 150°F.
3. Draw 6 hours at 1200°F. (Heat 64586)
4. Draw 6 hours at 1225°F. (Heat 53020)
5. Furnace cool from draw.

Dimensional measurements were made before and after heat treatment. Magnetic particle inspection following salvage heat treatment included hub, welds and entire gear rim. Eight Brinell hardness tests, 90° apart, on each edge were made per M.S. 3905F. Subsequently gear assemblies were cut into 3 pie sections to obtain macrospecimens of rim and rim welds and hub and hub welds 120° apart. Also removed were tensile specimens from hub, rib plates and rim, and impact specimens from rim.

Tests and Results

Impact tests of all heats supplied are listed in Table III. Additional impact test specimens were removed from Heat No. 64586 (Rims LB 180 and LB 188). Tests were made at elevated temperature (simulating service temperatures) and after a variety of heat treatments. Results are listed in Table IV. Confirmatory tests were made on Rim LB 180 at California State College. The small gain in impact strength resulting from retempering of Rim LB 188 to lower hardnesses and the appreciable gain in impact strength as a result of water quenching and drawing should be noted.

Results of hardness, tension and impact tests made on high speed rims LB 162 and LB 169 before and after salvage heat treatment are listed in Tables V and VI, respectively. The tensile strength properties of rim, hub and rib plates are excellent. Note that the impact strength on Rim LB 162 (Ht. 53020) has been increased from a Charpy V-notch impact strength of 22-33 ft-lbs. to 42-70 ft-lbs. and on Rim LB 169 (Ht 64586) to 42-66 ft-lbs. from the low values shown in Table IV.

Dimensional measurements made before and after salvage heat treatment indicated that all gear wheel assemblies from Heat No. 64586 except those finish machined could be salvage heat treated since sufficient machining stock remained. Dimensional changes were fairly uniform. Diametrical shrinkage varied from .027" maximum on journals to 1/16" maximum on rims. Total maximum indicator reading on rims was .017" and bow on rim from center to edges was no greater than 3/64".

Complete magnetic particle inspection of rims, welds and hubs revealed no evidence of cracks as a result of salvage heat treatment. Macro-etch specimens removed 120° apart to show soundness of welds joining rim to center plates and hub to center plates revealed no evidence of defects resulting from salvage heat treatment. (See Photographs 9521, 9522, 9527, and 9528. The welds were excellent with the exception of a few scattered flux inclusions resulting from welding.

Microstructure

Specimens were removed from rims before and after salvage heat treatment. The effect of water quenching and drawing versus oil quenching and drawing can readily be seen in Figure 1. Note the grain refinement and more uniform carbode distribution in the water quenched and drawn microstructure.

In order to confirm that rims LB 191 (Ser. 248140), LB 193 (Ser. 252494), LB 194 (Ser. 252495) and LB 195 (Ser. 253541) had been water quenched and drawn, their microstructures were studied. The microstructure of rim LB193 shown in Figure 1 confirms that they were water quenched and drawn.

Recommendations

The following recommendations are made as a result of this investigation:

A. Rims made from Heat No. 64586 should be salvaged by reheat treatment of wheel assemblies. This requires water quenching and drawing to improve impact properties of gear rims. The following gear rims are involved:

1.	LB 177	Slow Speed
2.	LB 167	" "
3.	LB 197	H.P.H.S.
4.	LB 171	" "
5.	LB 172	" "
6.	LB 173	" "
7.	LB 187	" "
8.	LB 189	" "
9.	LB 190	" "
10.	LB 175	L.P.H.S.
11.	LB 192	" "
12.	LB 170	" "
13.	LB 183	" "
14.	LB 184	" "
15.	LB 185	" "
16.	LB 186	" "

Additional Tests must be made on slow speed wheel LB 168 after trial heat treatment before proceeding with LB 177 and LB 167 above. If reheat treatment of slow speed wheels is satisfactory, it will be necessary to weld rim center subassembly before salvage heat treatment in order to prevent distortion of gear rim which would occur if it were quenched as a rim only.

B. Rims made from Heat No. 64586 which were oil quenched and drawn and cannot be salvaged by heat treatment must be replaced as they are unsuitable for service due to low impact strength. They are as follows:

	Rim	Type	Reason
1.	LB 168	Slow Speed	Finish machined
2.	LB 180	" "	Rim cracked in mfg.
3.	LB 174	H.P.H.S.	Finish machined
4.	LB 162	" "	Defective hub on finish machined assembly.
5.	LB 188	" "	Destroyed for metallurgical tests.
6.	LB 169	L.P.H.S.	Finish machined. Used for test.
7.	LB 163(Ht53150)	" "	Finish machined
8.	LB 164(Ht53150)	" "	Rejected for forging crack.

Rim LB 163 was rejected since impact tests indicated that Heat 53150 was borderline in strength.

C. Proceed with manufacture on gear assemblies using rims from all other heats as these are of a satisfactory impact strength level. These rims are as follows:

1.	LB 191	Slow Speed
2.	LB 166	" "
3.	LB 178	" "
4.	LB 176	" "
5.	LB 179	" "
6.	LB 181	" "
7.	LB 182	" "

Rim No. Heat No.	Temp. °F.	Std. Izod, Ft-lbs. Tang.	Long.	Charpy V-Notch, Ft-lbs. Tang.	Long.
LB 180	85	6	5	5	6
Ht. 64586		6	6	6	10
LB 188	70	8	8	9	6
Ht. 64586					8
LB 164	85	16	8.5		13
Ht. 53150					16
					16
					15 (70°F)
					21 (70°F)
	120				15
					16
					18
	160				15
					19
	200				19
					20
LB 165	70	15			
Ht. 75102		19			
LB 162					
Ht. 53020	75			22	
				31	
				33	
				28	
Ht. 64684	Room Temp.				
		30, 18, 25	17, 18, 22		
		27, 23, 22	20, 21, 15		
		31, 32, 24	22, 19, 14		
		30, 30, 31	19, 17, 19		
		Ave. - 27	Ave. - 19.5		

TABLE III - IMPACT TEST RESULTS - ALL HEATS-AS-RECEIVED

	Temp.	Izod-Std.		Izod-Rd.		Charpy V-Notch		Charpy Keyhole	
	°F	Ft.-lbs.		Ft.-lbs.		Ft.-lbs.		Ft.-lbs.	
		Tang.	Long.	Tang.	Long.	Tang.	Long.	Tang.	Long.
Original Tests- Rim LB 180	85°	6 6	5½ 6	3½ 4	5½ 7				
Transition Curve Tests - Rim LB 180 (Brinell 269)	85					5 6	6 10 12	7 8 15	
	120						9		
	160						12 10 12		
	200						15 16		
California State College Tests Rim LB 180	70	7 9				7	8	4 5 7	
Rim LB 188 As-Received (Brinell 269)	70	8	8	8 10	6½ 7	9	6 8	12 13½ 15	15 14 14
Rim LB 188 Retemper 1200°F (Brinell 255)	70			14 15	6½ 10	10 11	6 11½		
Rim LB 188 Retemper 1225°F (Brinell 241)	75	7 10	10 12	9 9 17 17½	9 15	6 8	8 9	20 21	15 16
Rim LB 188 (Test Pc.) 1525°F Water Quench Draw 4 hrs. 1250°F Air Cool (Brinell 217)				76 76	53 62	71 72	51 51		

TABLE IV - IMPACT TEST RESULTS - RIMS LB 180 and LB 188, HEAT NO. 64586

Material	Condition	Spec. No.	Tensile Strength psi	Yield Strength (0.2% offset) psi	Elong. in 2" %	Red. of Area %	Charpy V-Notch Impact Ft-lbs.
Rim LB 1162 Ht. 53020	As rec'd.	1. Tang.	117,000	95,000	23.5	58	22
		2 Tang.	115,000	91,000	22.5	57	31
		3 Tang.					33
		4 Tang.					28
	1550°F Water quench Draw 6 hrs. 1225°F	1 Tang.	114,600	91,400	25	63	70
		1 Long.	111,000	93,500	17.5	30.5	42
		2 Tang.					66
		2 Long.					46
Hub-Ser. 528-5 Item 1	Same as above	1 Long.	66,000	47,200	37	73	
		2 Long.	65,500	42,900	37.5	71	
Spec. A.Y. 24Y - 1 Sec. B Req'd. Min.			60,000	30,000	30	45	
Rib It. 6	Same as above	1	60,700	40,500	42.5		
		2	60,200	40,500	42		
Spec. A.Y. 24Y -31 Sec. B Req'd Min.			55,000	0.5 T.S.	1,550,000 / T.S.		

Brinell Hardness Tests

Material	Condition	1	2	3	4	5	6	7	8
Rim LB 162	As rec'd.	229	255	241	235	241	248	241	241
	1550°F water quench Draw 6 hrs. 1225°F	269	255	255	269	262	269	262	269

TABLE V - RESULTS OF TENSION, IMPACT AND BRINELL HARDNESS TESTS ON H.P.H.S. GEAR WHEEL LB 162

Material	Condition	Spec. No.	Tensile Strength psi	Yield Strength (0.2% offset) psi	Elong. in 2" %	Red. of Area %	Charpy V-Notch Impact Ft-lbs.
Rim LB 169	1550°F Water	1 Tang.	109,500	90,000	25.5	65	55
Ht. 64586	quench	2 Tang.					64
	Draw 6 hrs.	3 Tang.					66
	1200°F	4 Tang.					64
		1 Long.	106,000	86,500	23	55	42
		2 Long.					47
		3 Long.					57
		4 Long					45
Hub-Ser. 528-3	Same as above	1 Long	64,500	40,500	38.5	69	
Item 1		2 Long	65,500	44,200	37.5	75	
Spec. A.Y. 24Y - 1 Sec. B Req'd. Min.			60,000	30,000	30	45	
Rib, Item 6	Same as above	1	60,000	41,500	46.5		
		2	61,000	41,200	48		
Spec A.Y. 24Y - 31 Sec. B Req'd. Min.			55,000	0.5 T.S.	$\frac{1,550,000}{\text{T.S.}}$		

Brinell Hardness Tests

Material	Condition	1	2	3	4	5	6	7	8
Rim LB 169	As rec'd.	262	269	255	262	255	262	255	269
	1550°F Water quench Draw 6 hrs. 1200°F	255	255	262	262	235	229	229	241

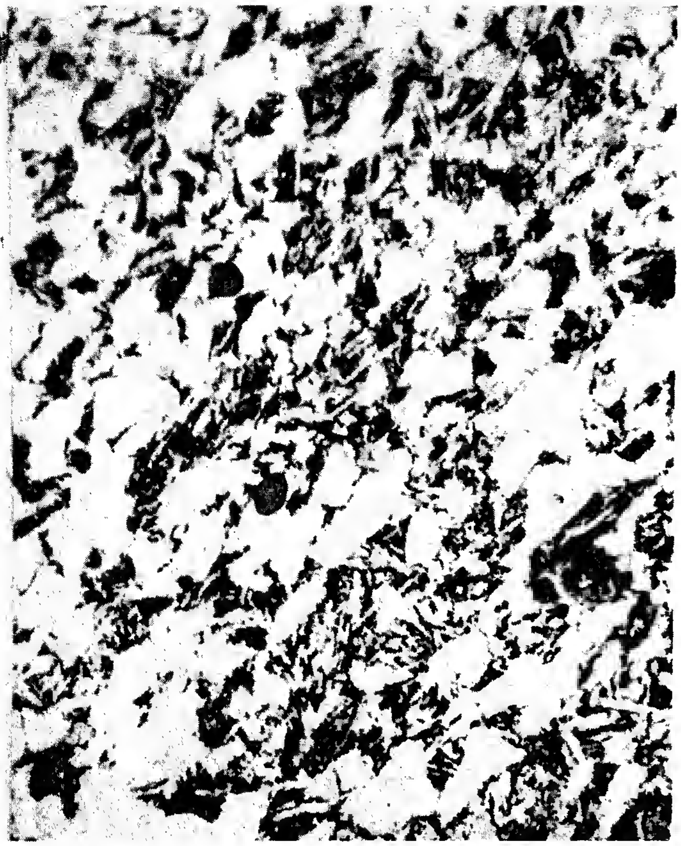
TABLE VI - RESULTS OF TENSION IMPACT AND BRINELL HARDNESS TESTS ON L.P.H.S. GEAR WHEEL LB 169

Material	Condition	Spec. No.	Tensile Strength psi	Yield Strength (0.2% offset) psi	Elong. in 2" %	Red. of Area %	Charpy V-Notch Impact Ft-lbs.
S.S. Rim LB 168 Ht. 64586 Ser. 238598	1575°F Water Quench Draw 6 hrs. 1240°F	1 Tang.	102,000	90,000	27	67.7	87
		2 Tang.					92
		3 Tang.					96
		1 Long.	95,000	80,000	21.5	50.4	99
		2 Long.					88
		3 Long.					52.5
Hub, Item 1	Same as above	1 Tang.	73,500	44,000	32.5	43.5	
Spec. A.Y. 24 Y - 1 Sec. B Req'd. Min			60,000	30,000	25	40	
Center plate Item 6	Same as above	1	57,500	39,500	41.5	76	
		2	55,000	35,000	39	74	
Spec. A.Y. 24Y - 31 Sec. B Cl. B Req'd Min.			55,000	0.5 T.S.	1,550,000 / T.S.		

Brinell Hardness Tests

Material	Condition	1	2	3	4	5	6	7	8
Rim LB 168	As rec'd.	241	255	255	255	269	255	269	269
	1575°F Water Quench Draw 6 hrs. 1240°F	217	217	212	223	229	241	229	229

TABLE VII - RESULTS OF TENSION, IMPACT AND BRINELL HARDNESS TESTS ON SLOW SPEED GEAR WHEEL LB 168 (same type of gear as in exhibit 1).



2% Nital Etch 500 X
As-Received
(Oil Quenched and Drawn)

2% Nital Etch 500 X
Water Quenched and Drawn

MICROSTRUCTURES OF RIM LB 170 (Heat 64586)

2% Nital Etch 500 X
Microstructure of Rim LB 193

As-Received (Water Quenched and Drawn)

Fracture of a Marine Gear (C)

It wasn't until 1966, when Consolidated phased out its San Diego plant and moved its operations to Long Beach, that Mr. Reynolds ran into the gear problem again. Since his last experience with gears during the period from 1954 and 1955, all his recommendations had been adopted and the gears were now being welded together with double J, fillet reinforced welds and the rims were being ordered from another manufacturer with better quenching facilities who was able to meet Consolidated's impact strength requirement.

"Although these recommendations had been adopted," Mr. Reynolds explained, "we would still find an occasional gear with noticeable cracks in it. The damaged rims were stress relieved now before the cracks were repaired, so we didn't have any 'exploding' gears like we did back in 1954, but it still took a lot of time to repair them. We watched how the gears were being welded together, and we noticed that the welders tended to let the preheat drop before they started welding. They had to lean inside the gear to weld the inside J welds, and I guess the 400° preheat made it pretty uncomfortable for them. They were probably inclined to let it cool off a little to make the work more bearable, and I suspect that this was a major factor in our problem."

"Because it's so hard to control a thing like this, we have begun to look around for an economical way to reduce the temperature the welders have to work with. This can be done either by changing the gear rim material to one that doesn't need a preheat or welding the rims with an automatic welder."

"We need the preheat with our present steel," continued Mr. Reynolds, "because we are welding a medium carbon steel which develops a layer of brittle martensite around the weld without preheating. We could weld a low carbon steel easily enough without a preheat, but there are few low carbon steels that have the wear resistance necessary for our application, even after heat treating and tempering. We have run across one high strength

low carbon alloy weldable steel which appears to meet all of our impact and hardness requirements. It isn't a standard steel, however, and is quite a bit more expensive than the steel we're now using." For example, the material costs for a rim are about 11% higher for this high strength material than for Consolidated's standard alloy steel. However, Consolidated has found a medium carbon steel that might be satisfactory for rim use. It has found that ordinary 4130 steel provides a cheaper rim than the current rim material (costing about 14% less for the material), and has a greater hardenability. This means that the steel might be able to get by with a lower quench and still have the necessary hardness.

Automatic welding of the inside J and fillet welds was not considered because the inside joints could not all be reached with a welding machine. However, one of the engineers in Mr. Reynolds' section recently ran across an article in a 1965 trade journal about a submerged arc welding method used to line the interiors of pressure vessels with stainless steel.[1] This process was automatic and was capable of substantially higher deposition rates than ordinary submerged arc welding methods. He had heard about a patent[2] on a process to build up a "pad" of low carbon weld material on the inside of a gear rim before welding the center plates to the rim to avoid cracking. The idea was to preheat the rim, weld these "pads" to the rim with an automatic welding machine, stress relieve, then weld the cool rim to the plates conventionally. In this process, for which Consolidated could probably get a license on the patent, the welders wouldn't have to be anywhere within 10 feet of the rim while it was preheated.

The main reason that Consolidated didn't use this process in production was that the conventional submerged arc welding process built up these 1/2" deep by 3" wide "pads" slowly (about 22 lbs of weld material per hour) and was uneconomical. The new process, however, was capable of depositing over 66 lbs. of weld material per hour. Unlike the submerged

1. Ref: James E. Norcross, "Strip Cladding Speeds Stainless Overlay", Welding Engineer, October 1965.
2. Ref: Patent No. 2,756,607.

arc process which used a single wire as an electrode and weld material supply, the new process uses two metal strips for the weld layer supply. Again, an automatic welding machine is employed and one of the low carbon alloy strips is used as one of the electrodes. The other strip, however, is inserted into the arc area beneath the hot strip. In effect, insertion of the cold strip results in the arc melting weld metal to form the alloy layer instead of melting the base metal.

Consolidated is now making a study to see if it is economically advantageous to switch over to this new process. The study will involve comparing the costs of manufacturing the gears by the standard technique (including the added costs from repair of the cracked rims), and by the strip cladding method (using "pads").